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ESTIMATION OF FLOOD PROBABILITIES

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HYDRAULICS DIVISION

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ESTIMATION OF FLOOD PROBABILITIES

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SYNOPSIS

Data of annual maximum mean-daily flows at 159 long-record river-measurement stations are analyzed to determine the characteristics of the frequency distributions and the reliability of probability determinations made therefrom. It is shown that the logarithms of the flows are normally distributed, which fact makes applicable to flood-flow data a wealth of statistical procedures and criteria. An important result of the verification of this fact is the ease with which region-wide correlation analyses can be made, through which precise hydrologic determinations will be possible.

INTRODUCTION

The determination of exceedence probabilities of flood magnitudes is of fundamental importance in many design problems. Where adequate records are available, the simplest method of estimating such probabilities is by a frequency analysis of recorded flood flows. However, the method is presently limited in applicability because of the unreliability of extreme-frequency determinations. It is the purpose of the following analysis to measure the reliability of calculated flood-flow probabilities and to investigate means of increasing that reliability.

In the course of this investigation, it has become apparent that a comprehensive, nation-wide analysis of flood flows will be required in order to establish adequate criteria and procedures for flood-frequency determinations. The all-important prerequisite to such an analysis is the summarization of flood-frequency attributes common to all locations in the form of a characteristic function of flood-flow distributions. Although many theories have been advanced for determining this function, the writer knows of no theoretically complete and adequately documented exposition of a flood-flow distribution theory. Information furnished in the following analysis is presented with the hope that it will complete the accomplishment of this preliminary task insofar as peak flows are concerned.

Theoretical Distribution of Flood Flows

By far the most common function that is characteristic of continuous distributions of observed values, each value of which is the effect of the identical multitude of varying causes, is the normal distribution.[1] There have been many demonstrations that some distributions are fitted by the theoretical curve to virtual perfection. For this reason, the normal curve should ordinarily provide the best starting point in a search for the most representative function of a continuous variable.

In order for a variable to comply with the requirements of a normal distribution, it must be continuous, values near the mean must occur more frequently than extreme values, and it must range from minus infinity to plus infinity. The logarithms of flood flows are the values that most logically might comply with these requirements. Furthermore, for many years, there has been recognized a tendency for the logarithms of annual maximum flood flows to be normally distributed.[2] It is proposed to test this theory by use of the wealth of stream flow data collected and published by the U. S. Geological Survey. Inasmuch as characteristics of small samples vary fortuitously from those of the parent population, the principal problem to be solved is the determination of whether observed variations from the normal are sampling variations or are characteristic of the parent distribution (i.e. whether or not they can be expected to recur in a future series of events).

Analysis of Goodness of Fit

The first step in the analysis of goodness of fit was the selection of 159 gaging stations, whose records are published regularly in U.S.G.S. Water Supply Papers. None of these stations were downstream of substantial control or diversion works during the period of record used. With few exceptions, all stations have 25 or more years of record and are located such that the center of tributary area is at least 50 miles from the center of tributary area for any other station used. Where drainage areas differed by a factor of 10 or more, the requirement of 50-mile separation was waived. Stations used are listed in Table 1, and locations of tributary-area centers are shown in Figure 1.

Secondly, a tabulation was made of all annual maximum mean-daily flows that occurred during the periods of record. Special caution was observed in order that values were not excluded because they were too large to record. If a gage was destroyed by a flood, an estimate from high-water marks was usually available. A few stations where reliable estimates were not available were eliminated from the original list, reducing it to the final list of 159 stations.

The third step consisted of tabulating the logarithms of all observed annual maximum mean-daily flows, and calculating the mean and standard deviation for each station. Standard deviations were computed in accordance with the equation:

$$\bar{S} = \sqrt{\frac{\Sigma(x)^2}{n-1}} \qquad (1)$$

in which x = deviation of a given logarithm from the mean of the logarithms for the station
n = number of years of record.

An example of this computation is given in Table 2. Capital X represents the logarithm of a single flow, and lower case x represents the deviation of a single logarithm from the mean (M) of the logarithms. The sum of the logarithms and the sum of the squares of the logarithms are obtained in a single cumulative operation of an automatic calculator. The square of the sum divided by the number of events is subtracted from the sum of the squares in order to obtain the sum of the squared deviations from the mean. This is simply a short-cut operation, which eliminates a large amount of tedious calculation. Note that in this case it was necessary to carry 7 places in the intermediate steps in order to obtain 4 in the results. The sum of the

squared deviations is divided by the number of events (less 1, because deviations are from the computed mean rather than from the true mean) in order to obtain the variance. The square root of the variance is the standard deviation (S).

In the fourth step, the numbers of observed values lying within ranges delineated by various percentages (30, 60, 90, etc) of the standard deviation from the mean were counted. The numbers counted were tabulated and compared with the numbers expected in each range for a normal distribution. This comparison is shown graphically in Figure 2, where a normal cumulative frequency curve is compared with that determined by the values counted as outlined above. The comparison is so close that it can be concluded at this point that the aggregate of the values for a great number of stations widely distributed geographically follows a normal distribution. The accepted chi-square test of goodness of fit cannot be applied strictly in a case such as this, inasmuch as not all of the values are entirely independent of each other.

In the fifth step, it is determined whether the indicated distribution functions of individual stations vary characteristically or randomly from normal. It is entirely possible that some of the regions are characterized by peculiarities of skew or kurtosis,[3] even though the aggregate is not. For this purpose, the 45 stations having 40 or more years of record were selected for special study. The latest 20 years of record and the preceding 20 years of record for each station were tabulated separately. Deviations from the 20-year mean were computed for each value (logarithm). Sums of the squares, cubes and fourth powers of the deviations were computed for each of the ninety 20-year records. Coefficients of dispersion, skew, and kurtosis were determined by the following equations:

$$S = \sqrt{\frac{\Sigma(x)^2}{n}} \qquad (2)$$

$$Sk = \frac{\Sigma(x)^3}{n\,S^3} \qquad (3)$$

$$K = \frac{\Sigma(x)^4}{n\,S^4} \qquad (4)$$

Computed values of mean, dispersion coefficient, skew coefficient and kurtosis coefficient are listed in Table 3. Coefficients of determination between the respective pairs of columns are .89 for dispersion, .01 for skew, and .00 for kurtosis. Thus, only one percent of the skew evidenced in one period was consistently evidenced in the second period. Kurtosis persistence is zero (to two places).

The results obtained in the above analysis are believed to constitute adequate proof that in the great majority of distributions of annual maximum mean-daily flow, the assumption of logarithmic normality is justified for all practical uses.

Graphical Presentation

For hydrologic design purposes and for simplicity in many applications, frequency distributions are most conveniently represented by cumulative frequency curves. For this purpose, recorded events are numbered in the order of descending magnitude and each magnitude is plotted against the relative frequency with which it is exceeded.

There is a lack of general agreement as to the proper method of plotting the points. One line of thought is that the largest event in 20 years has been

equalled or exceeded once in 20 years and should therefore be assigned an exceedence interval of 20 years. This reasoning is not rigorous, because it can similarly be reasoned that all events have been equal to or smaller than the largest recorded, giving it an exceedence interval of infinity.

The second line of reasoning is that the largest event is representative of largest events of other similar periods, i.e., that half of the 20-year periods at a location will have maximum events smaller than the one in question. This appears to be quite reasonable (accepting the inevitable assumption that the record is a random selection) and results in the conclusion that the largest event of a 20-year record will be exceeded in only half of all 20-year periods or somewhat oftener than once in 40 years. (Some 20-year periods may have 2 or more larger events.) The plotting positions given in Table 4 are based on this reasoning.

An example of graphical construction of a cumulative-frequency curve of annual flows is illustrated in Table 2 (b) and Figure 3. The logarithmic-probability grid was designed by Hazen such that a cumulative-frequency curve of a logarithmic-normal distribution would plot as a straight line. The line of best fit determined in Table 2 (a) is obtained simply by plotting the antilogarithm of the computed mean at 50 percent and the antilogarithm of the sum of the mean and standard deviation of 15.87 percent. The line determined by these two points is theoretically the best possible estimate of the true relation, judging by the plotted data only.

Of course, it is not necessary to plot such a curve simply to establish a frequency value. Values computed analytically are given in Table 2 (c) and should agree exactly with those read from Figure 3.

Accuracy of Individual Determinations

The determination that flood flows can be expressed as a normal distribution function makes possible the application to hydrology of reliability criteria developed by Student[4] and others. Student showed that the distribution of errors of calculated means from true means follows a particular law represented by his "t-distribution". Similarly, he presented criteria for describing the distribution of calculated values of dispersion relative to the true value (developed by Pearson and known as the "chi-square distribution").

Inasmuch as the true value of a statistic of a continuous variable never can be determined exactly, it never will be known how much a calculated value differs from the true value. However, limits on either side of the true value can be established within which any desired percentage of calculated values will lie. This percentage will be determined as a matter of policy in any particular application, but for convenience of discussion, a value of 90 percent will be used in the following illustrations. Five percent of the values will lie outside of each of the limits.

The error of a calculated mean is expressed as the following function of the calculated standard deviation:

$$M - \mu = \frac{t\,\overline{S}}{\sqrt{n}} \qquad (5)$$

in which, M = calculated mean
μ = true mean
t = function developed by Student

The value of $(M - \mu)$ calculated by use of Equation (5) is exceeded with the same frequency that the adopted value of t is shown by an appropriate table[3]

to be exceeded (disregarding sign). Positive values of $(M - \mu)$ or $(\mu - M)$ are exceeded with half that frequency.

Similarly, the error of a calculated standard deviation is expressed as the following function of the calculated standard deviation:

$$\bar{S} - \sigma = \left(1 - \sqrt{\frac{n-1}{X^2}}\right) \bar{S} \qquad (6)$$

in which, σ = true standard deviation
X^2 = function developed by Pearson

The value of $(\bar{S} - \sigma)$ calculated by use of Equation (6) is exceeded with the same frequency that the value of X^2 is shown by an appropriate table[3] not to be exceeded.

Knowing the error of the mean value and the error of the standard deviation, it is possible to compute the error of a value at any number (x) of standard deviations from the mean by the equation:

$$\delta_x = \sqrt{(M - \mu)^2 + (x\bar{S} - x\sigma)^2} \qquad (7)$$

Suppose it is desired to determine the amount to be added to the one-percent flood calculated from a 20-year record so that the resulting value has only one chance in 20 (5 percent) of being smaller than the true one-percent value. From published tables, the values of t and X^2 corresponding to .05 for a series of 20 events are 1.729 and 10.117, respectively. From equation (5), $(M - \mu) = -.387\ \bar{S}$. From Equation (6), $(\bar{S} - \sigma) = -.370\ \bar{S}$. A table[3] of normal-curve values will show that for the one-percent value, x = 2.326. From equation (7), $\delta_x = .944\ \bar{S}$. A common value of $\bar{S}$ for logarithms of flood flows is .2, in which case δ_x would be .189. Addition of this logarithm is equivalent to addition of 55 percent to the arithmetic equivalent of the calculated one-percent value.

By similar calculations, the errors of a one-percent flood exceeded with various likelihoods when using a 5-year record were calculated and plotted as Figure 4. To illustrate the applicability of this relationship, records of the 10 stations having 50 or more years of record were divided into 5-year periods. Inasmuch as the error of the one-percent value obtained using the entire record in each case is small compared with the usual errors obtained using 5-year records, the use of the long-period determination as the true value should not introduce great error for the purpose of this test. Accordingly, one-percent values were determined using each of the 123 five-year periods, and errors measured from the assumed true values were tabulated in terms of the standard deviation calculated from the 5-year record. These results were arranged in the order of descending magnitude and plotted as a cumulative frequency curve in Figure 4. The comparison with the theoretical curve appears to be satisfactory.

A less direct but more rigorous test (inasmuch as it does not involve the assumption of a true value) is illustrated in Figure 5. The data of Table 2 were used to calculate one-percent floods for each 20-year record. The difference of each pair of determinations was divided by the average standard deviation of the two periods. The resulting values were plotted as a cumulative frequency curve and compared to the theoretical distribution. The error theory appears to apply perfectly.

From the information presented thus far, it is believed that the theoretical dependability criteria which are accepted generally in statistical work are fully applicable in the treatment of runoff data. As a practical illustration of the general magnitudes of errors involved, Figure 6 shows the 1-in-20

limits of error for various record lengths and frequency determinations where the calculated standard deviation is .20. The lower curves delineate the limits below which the true values will fall with a frequency of once in 20. The upper curves delineate the limits above which the true values will fall with a frequency of once in 20. Between the corresponding two curves, 9 out of 10 of the true values will fall. It can be seen, for example, that when the standard deviation calculated from a 50-year record is .20, the true 50-percent (mean) value has 19 chances in 20 of being smaller than 1.11 times the calculated value, and the true 1-percent value (100 year flood) has 19 chances in 20 of being smaller than 1.27 (3.72/2.92) times the calculated value.

Figure 7 is presented for the conveniences of those who are accustomed to thinking in terms of probable error. In this case, there is one chance in two of the true value lying between corresponding upper and lower curves, and one chance in 4 that it will lie above the upper curve.

Calculation of error-limit curves can be facilitated by the use of Table 5, in which values of probable error and 1-in-20 error in terms of the standard deviation are given for various exceedence frequencies and lengths of record.

Need for Region-wide Analyses

It takes only a glance at Figure 6 to show that results obtainable from data of an individual station are wholly inadequate to the needs of flood-control design. This fact has of course been recognized for years. Enveloping curves have been developed, intricate hydrologic analyses have been devised, and extensive meteorological studies have been carried out for the purpose of combining information from many areas and regions for the solution of any specific problem. It is necessary to analyze flood-frequency characteristics on a region-wide or country-wide basis before adequately precise and reliable determinations are possible.

This problem should be much simpler than the problems that have already been attacked by hydrologists, inasmuch as all of the information required for the construction of a cumulative frequency curve is summarized in two values, i.e. the mean and the standard deviation. These values must be correlated with drainage area characteristics, geographic location, meteorological characteristics, etc. The results of such an analysis should make possible increasingly accurate determinations for all streams, even for those where good records are available.

Some valuable discussion on the factors to be considered in a regional analysis is included in the paper and subsequent discussions on "Stream Flow Variability" by E. W. Lane and Kai Lei.[5] Error criteria based on Equations (5) and (6) are presented graphically in Figure 8 for convenience in making regional studies.

Additional Reliability Considerations

The analysis developed so far deals with determinations and accuracy based on various theories of sampling. Allowances have not been made for errors of stream-flow measurements and possible inadequacies of sampling.

Systematic errors in measurement will generally result in increased error of the calculated mean, but will not always affect the accuracy of the standard deviation. Their effects should be largely eliminated in a proper regionalized study.

Erratic errors in measurement will affect the accuracy of both of the calculated values. However, the effects are much smaller than it might seem.

As an example, suppose the largest flood of the 20 shown in Table 4 were actually 25 percent larger than was measured. Correcting for this would change the mean from 4.944 to 4.949 and the standard deviation from .205 to .215, which would increase the calculated one-percent (100-yr) flood by a factor of .07.

The thesis of normality, as applied here, involves the assumption that the effects of factors capable of producing a large event are adequately experienced in the record. In some cases, this may not be true. Dam failures, earth slides, and debris jams constitute potential hazards which are not often indicated in the record. As a more common example, Colorado River at Grand Canyon experiences an annual flood from snow melt, which registers the maximum mean-daily flow almost every year. Yet, summer floods of considerable magnitude have been experienced. Their threat is in their rarity, and when estimating frequencies on the order of one percent or less, the possible effects of such floods should be considered. These conditions should result in a positive coefficient of skew in all cases where their effect is appreciable, which fact, coupled with the observation that there is no predominance of positive-skew cases, indicates that the consideration will be restricted to a relatively few areas. If such cases are found to exist, it will be necessary to estimate the effect by region-wide analysis, in which all of the extreme floods observed in the region of positive skew are compared with the number of extreme floods expected for the case of normality. This type of analysis would be advisable in any event as a test of normality.

Recorded data for most rivers are supplemented by historical data and high-water observations for great floods. In the determination of flood-frequency relationships for a given location, it is essential that all available pertinent information be utilized. This may be done by statistical means or as a matter of judgment. In this connection, it is pointed out that statistics given in the last two columns of Table 1 are for use in this analysis, but are not necessarily the best estimates, inasmuch as historical data were not considered. It is doubtful, however, that sketchy historical data would greatly modify values based on records of 25 or more years' length.

CONCLUSIONS

1. With rare exceptions, the logarithms of annual maximum mean-daily natural flow values are normally distributed.

2. Effective dependability criteria are readily available for application to individual flood-frequency determinations.

3. At best, flood-frequency determinations based on individual records are crude. It will be necessary to make region-wide analyses before precise determinations are possible.

REFERENCES

1. T. L. Kelley, Fundamentals of Statistics.
2. Hazen, Flood Flows.
3. Croxton and Cowden, Applied General Statistics.
4. Student, "The Probable Error of a Mean", Biometrika, v. 6, No. 1, p. 1., March 1908.
5. Proceedings of A.S.C.E., Sept. 1949 and Separate No. D-XVI.

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TABLE I -- RIVER STATION DATA

No.	River	Station Location	Drainage Area Sq.Mi.	Record Length Years	Computed Values M log.10	Computed Values S log.10
1	Machias R.	Whitneyville, Me.	457	34	3.748	.117
2	Mattawamkeag R.	Mattawamkeag, Me.	1,400	44	4.232	.136
3	Piscataquis R.	Dover-Foxfort, Me.	286	44	3.871	.180
4	Little Androscoggin R.	So. Paris, Me.	76	25	3.252	.215
5	Pemigewasset R.	Plymouth, N.H.	622	60	4.205	.166
6	Souhegan R.	Merrimack, N.H.	171	37	3.492	.196
7	M. Br. Westfield R.	Goss Heights, Mass.	53	36	3.172	.181
8	Housatonic R.	Falls Village, Conn.	632	34	3.772	.182
9	Schroon R.	Riverbank, N.Y.	527	39	3.697	.162
10	Hoosic R.	Eagle Bridge, N.Y.	510	37	3.912	.180
11	Rahway R.	Rahway, N.J.	41	25	2.881	.194
12	Raritan R.	Manville, N.J.	490	25	4.027	.155
13	E. Br. Delaware R.	Fishs Eddy, N.Y.	783	34	4.265	.152
14	Susquehanna R.	Harrisburg, Pa.	24,100	56	5.418	.147
15	Chemung R.	Chemung, N.Y.	2,530	43	4.596	.178
16	W. Br. Susquehanna R.	Williamsport, Pa.	5,680	52	4.939	.177
17	Juniata R.	Newport, Pa.	3,350	49	4.651	.169
18	Patuxent R.	Burtonsville, Md.	127	28	3.164	.219
19	Potomac R.	Point of Rocks, Md.	9,650	50	4.998	.243
20	Rappahannock R.	Fredericksburg, Va.	1,600	39	4.358	.278
21	Perkiomen Cr.	Frederick, Pa.	152	29	3.683	.120
102	James R.	Cartersville, Va.	6,240	48	4.800	.176
103	Appomattox R.	Mattoax, Va.	729	25	3.843	.255
104	Roanoke R.	Roanoke, Va.	388	49	3.754	.272
105	Dan R.	So. Boston, Va.	2,730	29	4.458	.181
106	Yadkin R.	Wilkesboro, N.C.	493	32	3.958	.279
107	Oconee R.	Dublin, Ga.	4,400	29	4.444	.222
108	Chattahoochee R.	West Point, Ga.	3,550	50	4.611	.210
109	Costanaula R.	Resaca, Ga.	1,610	50	4.302	.199
110	Tombigbee R.	Columbus, Miss.	4,490	29	4.589	.224
111	Pearl R.	Jackson, Miss.	3,100	27	4.374	.252
201	Allegheny R.	Red House, N.Y.	1,690	43	4.350	.143
202	Blacklick Cr.	Blacklick, Pa.	390	42	3.961	.179
203	West Fork R.	Butcherville, W. Va.	181	30	3.674	.153
204	Big Sandy Cr.	Rockville, W. Va.	200	34	3.813	.182
206	Kokosing R.	Millwood, Ohio	454	25	3.849	.231
207	Hocking R.	Athens, Ohio	944	31	4.091	.164
208	Reed Cr.	Grahams Forge, Va.	247	27	3.462	.218
209	Greenbrier R.	Alderson, W. Va.	1,360	50	4.415	.184
210	Meadow R.	Nallen, W. Va.	287	26	3.723	.137

TABLE I -- RIVER STATION DATA (Contd.)

No.	River	Station Location	Drainage Area Sq.Mi.	Record Length Years	Computed Values $\bar{M}$ log.10	Computed Values $\bar{S}$ log.10
211	Raccoon Cr.	Adamsville, Ohio	587	28	3.806	.157
212	Mad R.	Springfield, Ohio	485	32	3.686	.258
213	Kentucky R.	Winchester, Ky.	3,960	37	4.701	.120
214	Embarrass R.	Ste. Marie, Ill.	1,540	33	4.024	.263
215	W. Fk. White R.	Noblesville, Ind.	845	31	3.979	.229
217	Cumberland R.	Nashville, Tenn.	12,900	109	5.076	.101
218	S. Fk. Cumberland R.	Nevellsville, Ky.	1,260	30	4.626	.202
219	Red R.	Adams, Tenn.	678	26	4.052	.246
220	French Broad R.	Asheville, N.C.	945	51	4.140	.218
221	Davidson R.	Brevard, N.C.	40	25	3.043	.211
222	S. Fk. Holston R.	Bluff City, Tenn.	816	46	4.029	.174
223	Tuckasegee R.	Bryson City, N.C.	655	49	4.034	.203
224	Powell R.	Arthur, Tenn.	685	27	4.107	.165
225	Hiwassee R.	Murphy, N.C.	406	44	3.933	.219
226	Sequatchie R.	Whitwell, Tenn.	384	26	3.897	.191
227	Elk R.	Prospect, Tenn.	1,780	28	4.426	.170
228	Buffalo R.	Flat Woods, Tenn.	447	26	3.985	.281
229	Tennessee R.	Chattanooga, Tenn.	21,400	61	5.298	.130
301	Pike R.	Amberg, Wis.	250	32	2.998	.178
302	Fox R.	Berlin, Wis.	1,430	48	3.563	.173
303	Wolf R.	New London, Wis.	2,240	50	3.787	.194
304	Milwaukee R.	Milwaukee, Wis.	661	32	3.634	.284
306	Auglaize R.	Defiance, Ohio	2,330	26	4.305	.232
307	Canaseraga Cr.	Dansville, N.Y.	153	28	3.376	.186
308	St. Regis R.	Brasher Center, N.Y.	616	33	3.840	.126
401	Red R. of North	Grand Forks, N. Dak.	30,100	49	4.040	.328
402	Red Lake R.	Crookston, Minn.	5,280	45	3.689	.310
403	Pembina R.	Neche, N. Dak.	3,080	39	3.029	.413
404	Mississippi	Clinton, Iowa	88,600	73	5.113	.153
405	Crow R.	Rockford, Minn.	2,520	25	1.328	.463
406	Minnesota R.	Mankato, Minn.	14,900	44	4.036	.371
407	Black R.	Neillsville, Wis.	756	37	4.030	.270
408	LaCrosse R.	W. Salem, Wis.	412	33	3.243	.206
409	Root R.	Houston, Minn.	1,270	25	3.908	.260
410	Turkey R.	Garber, Iowa	1,530	25	4.082	.180
411	Maquoketa R.	Maquoketa, Iowa	1,550	33	4.058	.222
412	Rock R.	Como, Ill.	8,700	32	4.366	.232
413	Sugar R.	Brodhead, Wis.	529	32	3.520	.305
414	Iowa R.	Marshalltown, Iowa	1,530	25	3.775	.326
415	Cedar R.	Cedar Rapids, Iowa	6,640	43	4.314	.275

TABLE I -- RIVER STATION DATA (Contd.)

No.	River	Station Location	Drainage Area Sq.Mi.	Record Length Years	Computed Values M log.10	Computed Values S log.10
416	Skunk R.	Augusta, Iowa	4,290	31	4.252	.266
417	Des Moines R.	Keosauqua, Iowa	13,900	39	4.550	.210
418	Kankakee R.	Momence, Ill.	2,340	32	3.739	.163
419	Fox R.	Dayton, Ill.	2,570	32	3.940	.252
420	Mackinaw R.	Green Valley, Ill.	1,100	25	3.833	.324
421	Sangamon R.	Monticello, Ill.	550	36	3.639	.304
422	Big Muddy R.	Plumfield, Ill.	753	36	3.837	.325
424	St. Croix R.	Danbury, Wis.	1,550	32	3.611	.171
502	Madison R.	W. Yellowstone, Mont.	419	29	3.054	.123
508	Lodge Cr.	International Bdy.	797	36	3.050	.348
519	Republican R.	Clay Center, Kan.	24,600	40	4.078	.349
520	Kansas R.	Topeka, Kan.	56,700	40	4.587	.313
522	Solomon R.	Niles, Kan.	6,770	35	3.776	.346
523	Big Blue R.	Randolph, Kan.	9,100	28	4.262	.310
524	Grand R.	Gallatin, Mo.	2,250	25	4.315	.303
525	Medicine Cr.	Galt, Mo.	225	25	3.518	.314
526	South Grand R.	Brownington, Mo.	1,660	25	4.079	.358
527	Yellowstone R.	Glendive, Mont.	66,100	44	4.846	.178
601	Meramec R.	Eureka, Mo.	3,788	25	4.505	.284
602	St. Francis R.	Patterson, Mo.	956	25	4.369	.326
603	James R.	Galena, Mo.	987	25	4.143	.320
604	Eleven Point R.	Bardley, Mo.	793	25	3.756	.467
606	Walnut R.	Winfield, Kan.	1,890	25	4.218	.341
607	Neosho R.	Iola, Kan.	3,800	48	4.317	.303
609	Petit Jean Cr.	Danville, Ark.	760	29	4.132	.346
610	Sulphur R.	Darden, Tex.	2,750	23	4.479	.313
651	Sabine R.	Logansport, La.	4,860	39	4.225	.319
652	Neches R.	Rockland, Tex.	3,540	40	4.146	.364
653	Trinity R.	Oakwood, Tex.	12,800	34	4.509	.371
654	Brazos R.	Waco, Tex.	19,300	42	4.666	.286
655	Little R.	Cameron, Tex.	7,030	30	4.475	.451
565	Colorado R.	Ballinger, Tex.	5,340	38	4.104	.323
657	N. Llano R.	Junction, Tex.	914	31	3.401	.755
658	Guadalupe R.	N. Braunfels, Tex.	1,666	31	3.810	.532
663	Conejos R.	Mogate, Colo.	282	44	3.385	.145
704	Blue R.	Dillon, Colo.	129	37	2.815	.131
709	Elk R.	Clark, Colo.	206	27	3.383	.119
710	Ashley Cr.	Vernal, Utah	101	29	2.879	.196
711	Huntington Cr.	Huntington, Utah	188	34	2.774	.224
716	Tonto Cr.	Roosevelt, Ariz.	678	34	3.547	.499

TABLE I — RIVER STATION DATA (Contd.)

No.	River	Station Location	Drainage Area Sq.Mi.	Record Length Years	Computed Values M $\log_{10}$	Computed Values S $\log_{10}$
752	Blacksmith Fk.	Hyrum, Utah	260	33	2.570	.351
753	Weber R.	Oakley, Utah	163	43	2.243	.185
754	Spanish Fk.	Thistle, Utah	490	30	2.685	.206
757	W. Walker R.	Coleville, Calif.	182	40	3.197	.187
760	Chewaucan R.	Paisley, Ore.	275	34	2.813	.269
761	Silvies R.	Burns, Ore.	934	31	3.954	.349
801	Santa Ysabel Cr.	Mesa Grande, Calif.	58	22	2.613	.585
803	Santa Ana R.	Mentone, Calif.	195	50	2.780	.642
804	Waterman Cn. Cr.	Arrowhead Springs, Calif.	5	30	1.581	.426
806	San Gabriel R.	Azusa, Calif.	211	38	3.296	.668
807	L. Santa Anita Cr.	Sierra Madre, Calif.	2	30	1.117	.601
808	Arroyo Seco	Soledad, Calif.	241	45	3.580	.390
809	Kern R.	Bakersfield, Calif.	2,420	49	3.571	.290
810	Tule R.	Porterville, Calif.	266	45	3.156	.454
811	Kings R.	Piedra, Calif.	1,690	51	4.114	.217
812	N. Fk. Kings R.	Cliff Camp, Calif.	174	25	3.415	.202
813	Tenaya Cr.	Yosemite, Calif.	47	32	2.894	.212
816	N. Fk. Feather R.	Bidwell Bar, Calif.	1,350	35	4.147	.342
817	Oregon Cr.	N. San Juan, Calif.	35	35	3.033	.290
901	Quinault R.	Quinault Lake, Wash.	264	31	4.239	.173
902	S. Fk. Skykomish R.	Index, Wash.	355	37	4.246	.218
903	Columbia R.	Birchbank, B.C.	34,000	34	5.354	.094
904	Kootenai R.	Libby, Mont.	10,200	36	4.751	.157
906	St. Joe R.	Calder, Idaho	1,080	25	4.116	.211
934	Boise R.	Twin Springs, Idaho	830	36	3.759	.160
935	Salmon R.	Whitebird, Idaho	13,600	34	4.733	.148
936	Grande Ronda R.	La Grande, Ore.	678	36	3.431	.210
937	Clearwater R.	Kamaiah, Idaho	4,850	36	4.679	.136
961	Columbia R.	The Dalles, Ore.	237,000	77	5.782	.127
963	Crooked R.	Culver, Ore.	3,830	29	3.619	.172
964	Little Sandy R.	Bull Run, Ore.	22	27	3.129	.185
965	Willamette R.	Albany, Ore.	4,840	51	4.999	.206
966	McKenzie R.	McKenzie Bridge, Ore.	345	35	3.718	.198
967	Clackamas R.	Cazadero, Ore.	665	37	4.252	.227
968	Cowlitz R.	Packwood, Wash.	287	25	4.004	.184
969	Siletz R.	Siletz, Ore.	202	27	4.250	.150
970	Umpqua R.	Elkton, Ore.	3,680	41	4.846	.174
971	S. Fk. Coquille R.	Powers, Ore.	169	28	3.990	.155
973	S. Fk. Big Butte Cr.	Butte Falls, Ore.	131	29	2.807	.251

TABLE 2 — VALUES FROM TYPICAL 20-YEAR RECORD

(Willamette River at Albany, Oregon)

Table 2(a)

Water Year	Maximum M.O.F. c.f.s.	Maximum M.O.F. $\log_{10}$
1927	191,000	5.281
1928	74,000	4.869
1929	50,800	4.706
1930	84,100	4.925
1931	108,000	5.033
1932	134,000	5.127
1933	90,000	4.954
1934	70,200	4.846
1935	72,600	4.861
1936	120,000	5.079
1937	124,000	5.093
1938	92,600	4.967
1939	58,900	4.770
1940	58,300	4.766
1941	40,100	4.603
1942	83,400	4.921
1943	210,000	5.322
1944	44,400	4.647
1945	71,200	4.852
1946	185,000	5.267
ΣX		98.889
M		4.944
$\Sigma(X)^2$		489.7495
$(\Sigma X)^2/n$		488.9517
$\Sigma(x)^2$		0.7978
$\Sigma(x)^2/n-1$		0.04199
$\bar{S}$		0.205

Table 2(b)

Annual Flows c.f.s.	Plotting Position %
210,000	3.4
191,000	8.3
185,000	13.2
134,000	18.1
124,000	23.0
120,000	27.9
108,000	32.8
92,600	37.7
90,000	42.6
84,100	47.5
83,400	52.5
74,000	57.4
72,600	62.3
71,200	67.2
70,200	72.1
58,900	77.0
58,300	81.9
50,800	86.8
44,400	91.7
40,100	96.6

$M + \bar{S} = 5.149$.
Antilog. = 141,000.
Plot at 15.9%.

$M - \bar{S} = 4.739$.
Antilog. = 54,800.
Plot at 84.1%.

Table 2(c)

Exceedence interval	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Exceedence frequency	0.50	0.20	0.10	0.04	0.02	0.01
$\bar{S}$ multiples above mean	0	0.842	1.282	1.751	2.054	2.326
Diff. from mean (log.)	0	0.173	0.263	0.359	0.421	0.477
Mean (log.)	4.944	4.944	4.944	4.944	4.944	4.944
Computed flow (log.)	4.944	5.117	5.207	5.303	5.365	5.421
Computed flow (cfs)	87,900	131,000	161,000	201,000	232,000	264,000

TABLE 3 -- COMPARISONS OF STATISTICS FOR SUCCESSIVE PERIODS

STA	Latest 20 Years M	S	SK	K	Preceding 20 Years M	S	SK	K
2	4.219	.125	.584	2.60	4.240	.153	.463	3.02
3	3.816	.137	.789	4.04	3.888	.199	.485	2.47
5	4.200	.222	1.007	3.51	4.221	.125	.018	2.25
14	5.397	.169	.857	3.53	5.421	.127	-.539	2.17
15	4.620	.196	.121	2.19	4.572	.167	-.960	2.87
16	4.909	.197	.751	2.87	4.986	.138	-1.278	3.54
17	4.626	.195	1.549	5.41	4.666	.139	.309	2.54
19	5.030	.289	.156	2.68	4.969	.180	-.109	3.16
102	4.817	.225	-.194	2.45	4.783	.109	-.100	1.89
104	3.734	.259	.024	1.94	3.732	.271	-.950	2.78
108	4.588	.202	-.436	2.34	4.595	.228	.130	2.91
109	4.367	.212	.652	3.45	4.332	.192	.200	2.03
201	4.350	.131	.478	2.40	4.350	.151	.114	1.64
202	3.941	.193	.912	3.51	3.975	.162	.050	2.67
209	4.421	.197	-.051	2.86	4.382	.196	-.129	2.02
217	5.072	.129	-.173	2.10	5.058	.090	-.392	2.41
220	4.085	.203	.322	2.56	4.118	.226	1.456	5.12
222	3.975	.174	-.705	3.35	4.051	.144	-.105	1.93
223	3.971	.194	.473	2.60	4.036	.210	-.468	2.84
225	3.861	.198	.185	1.84	3.960	.209	-.683	2.46
229	5.288	.127	-.416	3.08	5.253	.123	-.537	3.26
302	3.549	.200	-.552	2.81	3.600	.155	.091	1.62
303	3.831	.192	-.933	3.50	3.803	.186	.037	2.11
401	3.944	1.006	-.630	2.70	4.069	.969	-.566	2.38
402	3.605	.305	-.945	2.94	3.722	.294	-.615	3.68
404	5.067	.153	-1.220	4.48	5.086	.137	.366	2.16
406	3.954	.339	-.967	3.61	4.067	.390	-.401	2.15
415	4.284	.333	-.484	3.05	4.334	.188	.364	2.95
519	4.092	.342	.922	3.56	4.063	.346	.336	1.66
520	4.586	.358	-.248	1.87	4.588	.252	.412	2.31
527	4.777	.173	-.681	3.54	4.908	.168	-1.220	4.59
607	4.324	.351	-.687	2.65	4.280	.239	.278	2.42
652	4.186	.323	.312	1.84	4.106	.389	-.593	2.18
654	4.685	.218	.737	2.82	4.622	.334	.098	1.56
663	3.329	.141	-.444	2.16	3.421	.128	.713	4.07
753	3.148	.164	-.750	3.53	3.372	.139	.019	2.36
757	3.143	.185	.727	5.34	3.250	.168	-.155	3.39
803	2.751	.665	.313	2.43	2.832	.658	-.122	2.07
809	3.562	.319	.108	2.57	3.627	.280	.293	3.43
810	3.125	.464	-.056	1.98	3.120	.451	-.270	1.71
811	4.079	.229	.362	2.96	4.103	.192	-.693	3.84
961	5.720	.141	-.602	2.11	5.783	.090	-.638	2.77
965	4.944	.200	.287	2.29	5.016	.198	-.193	2.16
970	4.869	.176	.479	2.44	4.846	.148	-.167	2.42
808	3.576	.375	-1.340	4.60	3.620	.426	-.204	1.67

TABLE 4 -- PLOTTING POSITIONS
(percent)

	Number of Events															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	m
	50.0	29.3	20.7	15.9	13.0	10.9	9.4	8.3	7.4	6.7	6.1	5.6	5.2	4.8	4.5	1
			50.0	38.6	31.5	26.5	22.9	20.2	18.1	16.3	14.9	13.7	12.7	11.8	11.0	2
30	49.2	50.0			50.0	42.2	36.5	32.1	28.7	25.9	23.7	21.8	20.1	18.7	17.5	3
29	47.5	48.3	49.1	50.0			50.0	44.0	39.4	35.6	32.4	29.8	27.6	25.7	24.0	4
28	45.9	46.6	47.4	48.3	49.1	50.0			50.0	45.2	41.2	37.9	35.1	32.6	30.5	5
27	44.2	44.9	45.7	46.5	47.3	48.2	49.1	50.0			50.0	46.0	42.5	39.6	37.0	6
26	42.5	43.3	44.0	44.8	45.6	46.4	47.2	48.1	49.0	50.0			50.0	46.5	43.5	7
25	40.9	41.6	42.3	43.0	43.8	44.6	45.4	46.3	47.1	48.1	49.0	50.0			50.0	8
24	39.2	39.9	40.6	41.3	42.0	42.8	43.6	44.4	45.2	46.1	47.0	48.0	49.0	50.0		9
23	37.6	38.2	38.9	39.5	40.2	41.0	41.7	42.5	43.3	44.2	45.0	46.0	46.9	47.9	48.9	10
22	35.9	36.5	37.2	37.8	38.5	39.2	39.9	40.6	41.4	42.2	43.1	43.9	44.8	45.8	46.8	11
21	34.3	34.8	35.4	36.1	36.7	37.4	38.0	38.8	39.5	40.3	41.1	41.9	42.8	43.7	44.6	12
20	32.6	33.2	33.7	34.3	34.9	35.6	36.2	36.9	37.6	38.3	39.1	39.9	40.7	41.6	42.5	13
19	31.0	31.5	32.0	32.6	33.2	33.8	34.4	35.0	35.7	36.4	37.1	37.8	38.6	39.4	40.3	14
18	29.3	29.8	30.3	30.8	31.4	31.9	32.5	33.1	33.8	34.4	35.1	35.8	36.6	37.3	38.1	15
17	27.6	28.1	28.6	29.1	29.6	30.1	30.7	31.3	31.9	32.5	33.1	33.8	34.5	35.2	36.0	
16	26.0	26.4	26.9	27.3	27.8	28.3	28.9	29.4	30.0	30.5	31.1	31.8	32.4	33.1	33.8	
15	24.3	24.7	25.2	25.6	26.1	26.5	27.0	27.5	28.0	28.6	29.2	29.8	30.4	31.0	31.7	
14	22.7	23.1	23.5	23.9	24.3	24.7	25.2	25.7	26.1	26.6	27.2	27.7	28.3	28.9	29.5	
13	21.0	21.4	21.7	22.1	22.5	22.9	23.3	23.8	24.2	24.7	25.2	25.7	26.2	26.8	27.4	
12	19.4	19.7	20.0	20.4	20.7	21.1	21.5	21.9	22.3	22.8	23.2	23.7	24.2	24.7	25.2	
11	17.7	18.0	18.3	18.6	19.0	19.3	19.7	20.0	20.4	20.8	21.2	21.6	22.1	22.6	23.1	
10	16.1	16.3	16.6	16.9	17.2	17.5	17.8	18.2	18.5	18.9	19.2	19.6	20.0	20.5	20.9	
9	14.4	14.6	14.9	15.2	15.4	15.7	16.0	16.3	16.6	16.9	17.2	17.6	18.0	18.3	18.7	
8	12.7	13.0	13.2	13.4	13.6	13.9	14.1	14.4	14.7	15.0	15.3	15.6	15.9	16.2	16.7	
7	11.1	11.3	11.5	11.7	11.9	12.1	12.3	12.5	12.8	13.1	13.3	13.6	13.8	14.1	14.4	
6	9.4	9.6	9.8	9.9	10.1	10.3	10.5	10.7	10.9	11.1	11.3	11.5	11.8	12.0	12.3	
5	7.8	7.9	8.0	8.2	8.3	8.5	8.6	8.8	9.0	9.1	9.3	9.5	9.7	9.9	10.1	
4	6.1	6.2	6.3	6.4	6.6	6.7	6.8	6.9	7.0	7.2	7.3	7.5	7.6	7.8	8.0	
3	4.5	4.5	4.6	4.7	4.8	4.9	5.0	5.0	5.1	5.2	5.3	5.4	5.6	5.7	5.8	
2	2.8	2.8	2.9	3.0	3.0	3.1	3.1	3.2	3.2	3.3	3.4	3.4	3.5	3.6	3.7	
1	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.5	1.5	
m	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	
	Number of Events															

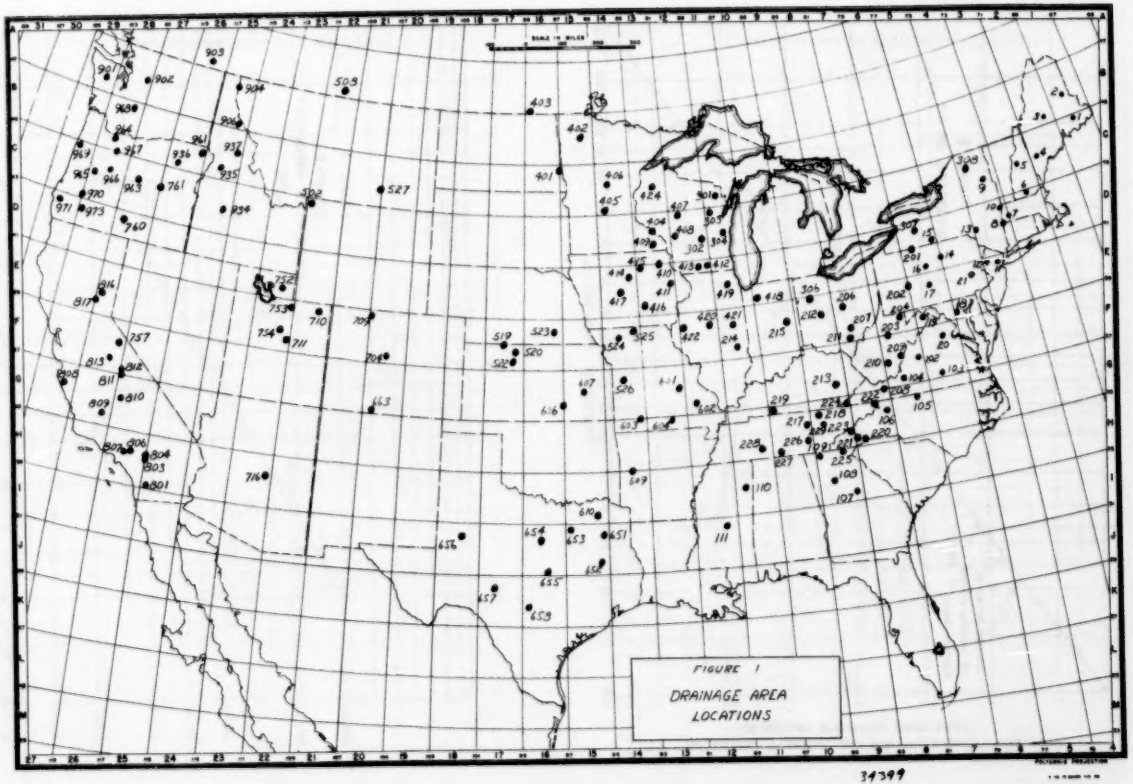
NOTE: Plotting position for m = 1 obtained from formula, $100\ (1 - .5^{1/n})$
Other plotting positions interpolated linearly to 50 percent
Plotting positions are symmetrical about 50 percent

TABLE 4 -- PLOTTING POSITIONS (Contd.)
(percent)

	Number of Events															
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	m
	4.2	4.0	3.8	3.6	3.4	3.2	3.1	3.0	2.8	2.7	2.6	2.5	2.4	2.4	2.3	1
	10.3	9.8	9.2	8.8	8.3	7.9	7.6	7.2	7.0	6.7	6.4	6.2	6.0	5.8	5.6	2
30	16.4	15.5	14.7	13.9	13.2	12.6	12.0	11.5	11.0	10.6	10.2	9.8	9.5	9.2	8.9	3
29	22.5	21.2	20.1	19.1	18.1	17.3	16.5	15.8	15.2	14.5	14.0	13.5	13.0	12.6	12.2	4
28	28.6	27.0	25.5	24.2	23.0	22.0	21.0	20.1	19.2	18.5	17.8	17.1	16.5	16.0	15.4	5
27	34.7	32.8	31.0	29.4	27.9	26.6	25.4	24.3	23.4	22.4	21.6	20.8	20.0	19.4	18.7	6
26	40.8	38.5	36.4	34.5	32.8	31.3	29.9	28.6	27.4	26.4	25.4	24.4	23.6	22.8	22.0	7
25	46.9	44.2	41.8	39.7	37.7	36.0	34.4	32.9	31.6	30.3	29.2	28.1	27.1	26.2	25.3	8
24		50.0	47.3	44.8	42.6	40.6	38.8	37.2	35.6	34.2	32.9	31.7	30.6	29.6	28.6	9
23	50.0			50.0	47.5	45.3	43.3	41.4	39.8	38.2	36.7	35.4	34.1	33.0	31.9	10
22	47.8	48.9	50.0			50.0	47.8	45.7	43.8	42.1	40.5	39.0	37.7	36.4	35.2	11
21	45.6	46.6	47.7	48.8	50.0			50.0	48.0	46.1	44.3	42.7	41.2	39.8	38.5	12
20	43.4	44.4	45.4	46.5	47.6	48.8	50.0			50.0	48.1	46.3	44.7	43.2	41.8	13
19	41.2	42.1	43.1	44.1	45.2	46.3	47.5	48.7	50.0			50.0	48.2	46.6	45.1	14
18	39.0	39.9	40.8	41.7	42.8	43.8	44.9	46.1	47.3	48.6	50.0			50.0	48.4	15
17	36.8	37.6	38.5	39.4	40.3	41.3	42.4	43.5	44.7	45.9	47.2	48.5	50.0			
16	34.6	35.4	36.2	37.0	37.9	38.9	39.8	40.9	42.0	43.1	44.3	45.6	47.0	48.5	50.0	
15	32.4	33.1	33.9	34.7	35.5	36.4	37.3	38.3	39.3	40.4	41.5	42.7	44.0	45.4	46.8	
14	30.2	30.8	31.6	32.3	33.1	33.9	34.8	35.7	36.6	37.6	38.7	39.8	41.0	42.1	43.6	
13	28.0	28.6	29.3	29.9	30.7	31.4	32.2	33.1	34.0	34.9	35.9	36.9	38.0	39.2	40.4	
12	25.8	26.3	27.0	27.6	28.3	29.0	29.7	30.5	31.3	32.1	33.0	34.0	35.0	36.1	37.3	
11	23.6	24.1	24.6	25.2	25.8	26.5	27.1	27.9	28.6	29.4	30.2	31.1	32.0	33.0	34.1	
10	21.4	21.8	22.3	22.9	23.4	24.0	24.6	25.3	25.9	26.6	27.4	28.2	29.0	29.9	30.9	
9	19.2	19.6	20.0	20.5	21.0	21.5	22.1	22.6	23.3	23.9	24.6	25.3	26.0	26.8	27.7	
8	17.0	17.3	17.7	18.1	18.6	19.0	19.5	20.0	20.6	21.1	21.7	22.4	23.0	23.8	24.5	
7	14.7	15.1	15.4	15.8	16.2	16.6	17.0	17.4	17.9	18.4	18.9	19.5	20.1	20.7	21.3	
6	12.5	12.8	13.1	13.4	13.8	14.1	14.5	14.8	15.2	15.7	16.1	16.6	17.1	17.6	18.1	
5	10.3	10.6	10.8	11.1	11.3	11.6	11.9	12.2	12.6	12.9	13.3	13.7	14.1	14.5	15.0	
4	8.1	8.3	8.5	8.7	8.9	9.2	9.4	9.6	9.9	10.2	10.4	10.7	11.1	11.4	11.8	
3	5.9	6.1	6.2	6.4	6.5	6.7	6.8	7.0	7.2	7.4	7.6	7.8	8.1	8.3	8.6	
2	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.7	4.8	4.9	5.1	5.2	5.4	
1	1.5	1.6	1.6	1.6	1.7	1.7	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.2	
m	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	

Number of Events

NOTE: Plotting position for m = 1 obtained from formula, $100\ (1 - .5^{1/n})$
Other plotting positions interpolated linearly to 50 percent
Plotting positions are symmetrical about 50 percent


903
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527
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973
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760
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817
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109
102
FIGURE 1
DRAINAGE AREA
LOCATIONS
34399

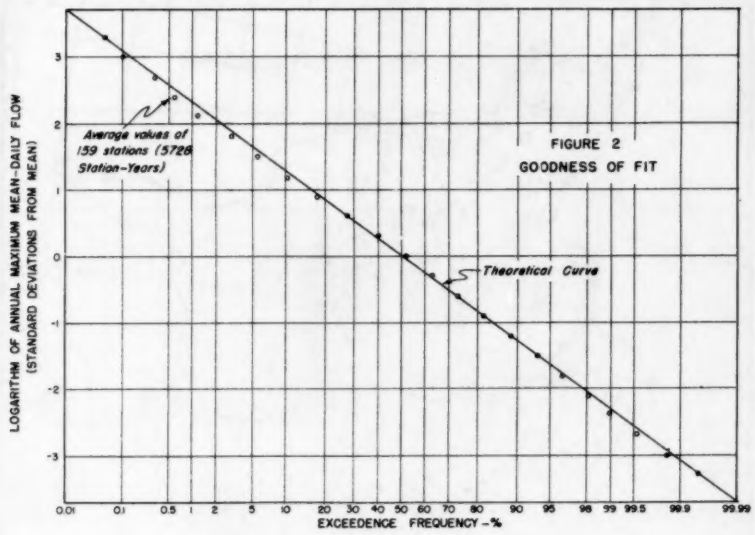

FIGURE 2
GOODNESS OF FIT

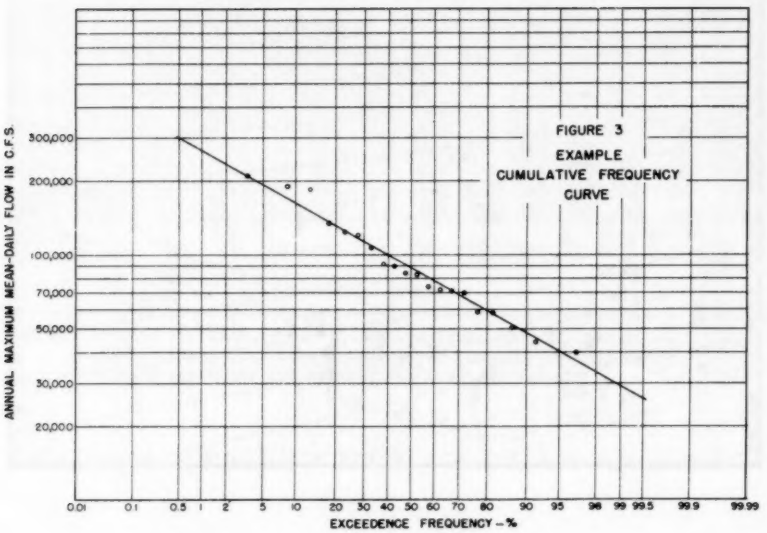

FIGURE 3
EXAMPLE
CUMULATIVE FREQUENCY
CURVE

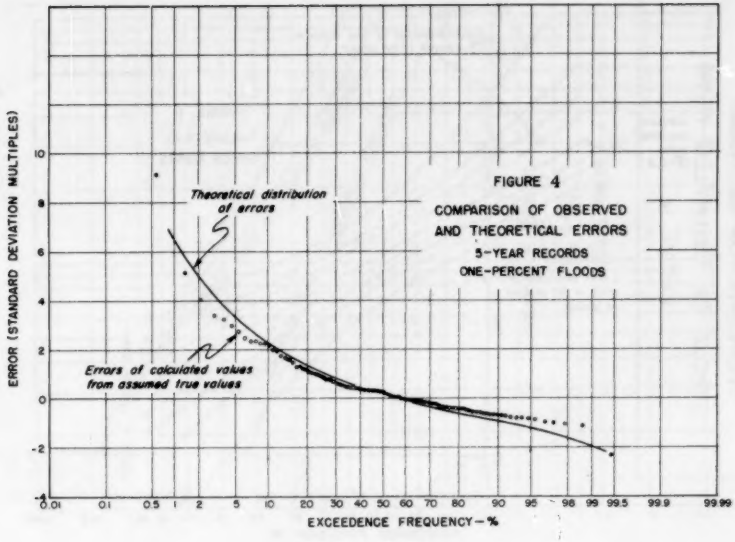

FIGURE 4

COMPARISON OF OBSERVED AND THEORETICAL ERRORS

5-YEAR RECORDS

ONE-PERCENT FLOODS

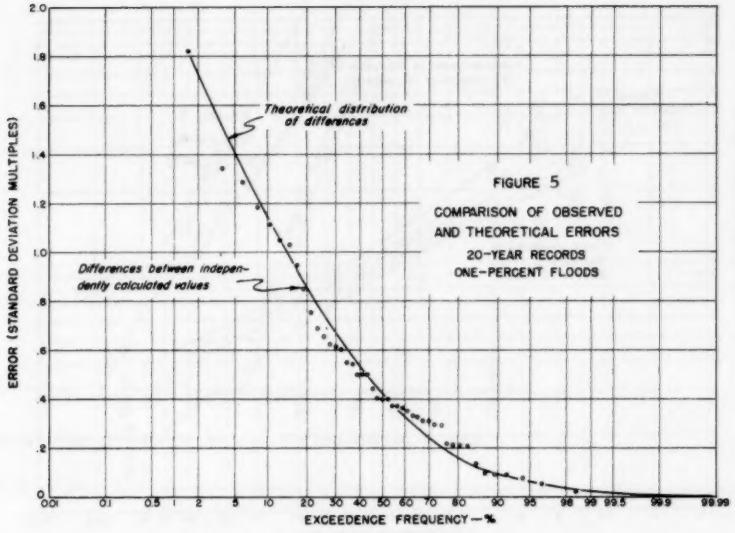

FIGURE 5

COMPARISON OF OBSERVED AND THEORETICAL ERRORS

20-YEAR RECORDS

ONE-PERCENT FLOODS

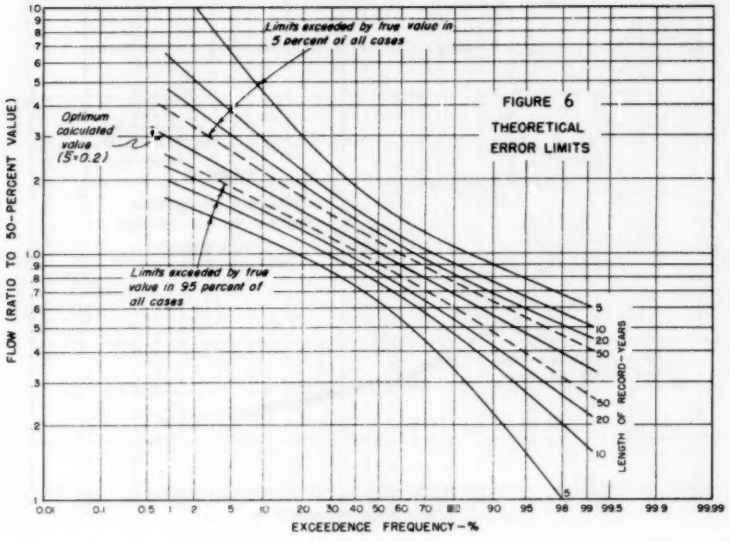

FIGURE 6
THEORETICAL
ERROR LIMITS

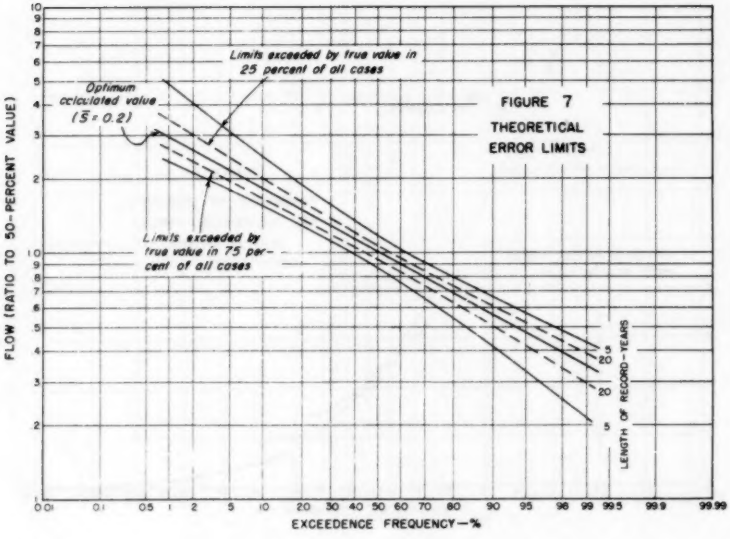
Limits exceeded by true value in 25 percent of all cases
Optimum calculated value (S=0.2)
Limits exceeded by true value in 75 percent of all cases
FLOW (RATIO TO 50-PERCENT VALUE)
EXCEEDENCE FREQUENCY—%
LENGTH OF RECORD—YEARS
20
20
5

FIGURE 7
THEORETICAL
ERROR LIMITS

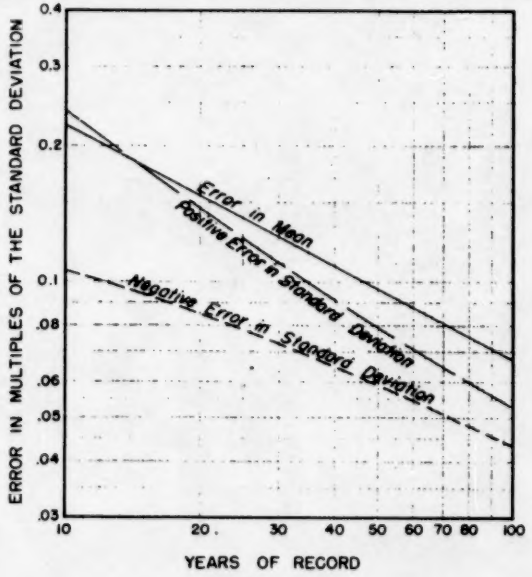

FIG. 8(a)
PROBABLE ERROR

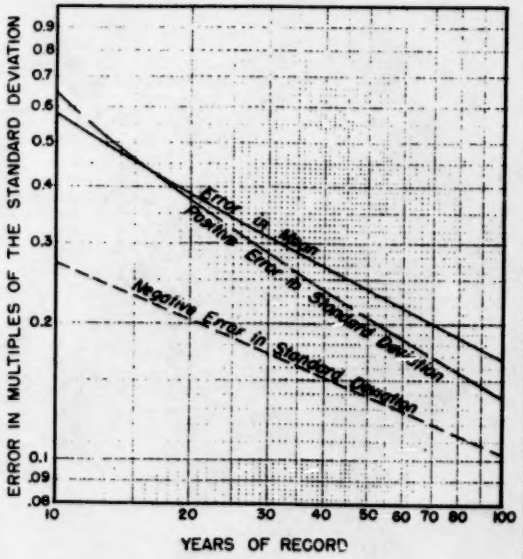

FIG. 8(b)
1-IN-20 ERROR

FIGURE 8
ERRORS OF ESTIMATED MEAN
AND STANDARD DEVIATION

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